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Sediment dynamics across gravel-sand transitions: Implications for river stability and floodplain recycling

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ABSTRACT

The gravel-sand transition (GST) is commonly observed along rivers. It is characterized by an abrupt reduction in median grain size, from gravel- to sand-size sediment, and by a shift in sand transport mode from wash load-dominated to suspended bed material load. We document changes in channel stability, suspended sediment concentration, flux and grain size across the GST of the Karnali River, Nepal. Upstream of the GST, gravel-bed channels are stable over hundred to thousand-year timescales. Downstream, floodplain sediment is reworked by lateral bank erosion, particularly during monsoon discharges. Suspended sediment concentration, grain size and flux reveal counterintuitive increases downstream of the GST. The results demonstrate a dramatic

change in channel dynamics across the GST, from relatively fixed, steep gravel-bed rivers with infrequent avulsion to lower gradient, relatively mobile sand-bed channels. The increase in sediment concentration and near-bed suspended grain size may be caused by enhanced channel mobility, which facilitates exchange between bed and bank material. These results bring new constraints on channel stability at mountain fronts, and indicate that temporally and spatially limited sediment flux measurements downstream of GSTs are more indicative of flow stage and floodplain recycling than of continental-scale sediment flux and denudation rate estimates.

INTRODUCTION

Downstream of mountain ranges, river bed sediment fines as channels flow onto lower gradient and laterally unconstrained landscapes (Sternberg, 1875). Sediment fining is a key component of sediment transport that underpins the dynamic nature of rivers, and is central to fluvial geomorphology and the depositional record it constructs. Downstream fining is attributed to size-selective sediment sorting (e.g. Ashworth and Ferguson, 1989; Paola et al., 1992a; Ferguson et al., 1996) and the mechanical breakdown (abrasion) of particles (e.g. Parker, 1991; Attal and Lavé, 2006; Dingle et al., 2017). Rivers commonly exhibit an abrupt transition in bed grain size, from gravel to sand, over a short downstream distance (e.g. Shaw and Kellerhals, 1982; Ferguson et al., 1996), termed the gravel-sand transition (GST). The development of GSTs has been attributed to a combination of size-selective sorting (e.g. Paola et al., 1992b; Wathen et al., 1995; Ferguson et al., 1996; Seal et al., 1997; Parker and Cui, 1998), abrasion of particles (e.g. Jerolmack and Brzinski, 2010) and abrupt changes in Reynolds number dependent sediment suspension thresholds (e.g. Venditti and Church, 2014; Lamb and Venditti, 2016). There is no generally accepted or universal theory for why GSTs develop.

Across GSTs, observed changes in channel morphology may help elucidate sediment transport adjustments and hint at possible causal mechanisms. Upstream of the GST, channels are typically mobile only at high flows (Dong et al., 2019). Downstream, channels are lower gradient and generally lower energy environments, but can be highly mobile when transporting large sediment loads (Montgomery et al., 1999). A reduction in channel gradient is also commonly observed at the GST (Sambrook-Smith and Ferguson, 1995; Ferguson, 2003) which, for stable channel conditions, should reduce sediment transport capacity. Progress in understanding how sediment transport adjusts across GSTs is limited by a paucity of direct observations.

In this paper we test for changes in sediment transport and channel mobility across a GST in the Karnali River, Nepal. We document sediment and channel dynamics at a range of time scales, including daily (suspended sediment samples), decadal (channel migration rates and patterns from satellite imagery) and century to millennia scales (dating of paleochannels). We complement these observations with calculations of sediment entrainment thresholds and frequency of bed mobility based on hydrological records to constrain timescales of channel mobility.

The Karnali River

The Karnali basin has a drainage area of 43,000 km^2 at the Himalayan mountain front. Its climate is dominated by the Indian summer monsoon between May and September, when the majority of annual water and sediment discharge occurs (Sinha and Friend, 1994). At the mountain front, near the town of Chisapani, the river exits a confined bedrock gorge and flows onto the alluvial Ganga Plain where it bifurcates into two branches (Fig. 1). At moderate flow in August 2017 (~4,500 m^3/s), discharge was observed to split between the two branches equally. The GST is ~40 km downstream of the mountain front, where there is a gradient break in the longitudinal river profile

(Fig. DR1). Over a distance of approximately 5 channel widths, the river bed composition changes from 85% gravel to >95% sand. The gravel reach gradient (0.001-0.002 m/m) is twice the sand reach gradient.

METHODS

Suspended sediment concentration and grain size data were collected at 5 sampling locations (Fig. 1) at 4 or 5 different depths, using a horizontal Van Dorn sampler deployed from an inflatable cataraft in August 2017 (Data Repository; Fig. DR2.1-2.5). Instantaneous sediment flux was calculated using two methods to evaluate uncertainty. We first calculated flux as the product of depth-averaged concentration and Acoustic Doppler Current Profile discharge measurement. We also calculated suspended sediment flux from the Rouse equation (see Data Repository). We regard the Rouse profile method as most reasonable as it uses the concentration data to estimate a profile that roughly fits the observations at lower depths, but does not incorporate the local and temporal variability inherent with measurements.

Paleochannels were identified on the Karnali fan (Fig. 1) and dated using optically stimulated luminescence (OSL) to determine when the channel was last active within the main channel network (see Data Repository). To constrain shorter-term rates of channel mobility, satellite imagery was analyzed for a 10 and 16 km reach upstream and downstream of the GST, respectively. Channel positions were mapped from images between 1984 and 2016 for the gravel-bed reach, and between 1975 and 2016 for the sand-bed reach.

The discharges required to move sediment in the gravel and sand reaches were calculated using a model based on the modified Chezy equation (Parker, 2004) and the Shields number (see Data Repository). For gravel reaches, we use a slope-dependent critical Shield's number (Lamb et al., 2008) and a value of 0.03 for sand reaches. Flood event return periods were calculated using gauged flow data fitted to Gumbel and Log Pearson Type III distributions. This assumes a stable climate over the time-intervals considered here (10^4 years) such that the magnitude of a given return-interval discharge is approximately constant. Holocene climate records suggest that the intensity of the Indian summer monsoon has gradually weakened over the past ~8 kyr, but has been relatively stable since ~5 kyr (Gupta et al., 2005; Dixit et al., 2014). The return period of our projected discharges may be under-estimated at $>10^3$ yr timescales.

Grain size measurements were taken from two gravel surfaces (Fig. DR4; 'gravel bar' and 'gravel bed') near the bifurcation using photo counting (Attal and Lavé, 2006; Whittaker et al. 2011; see Data Repository). Measurements were made of sand samples below the GST from material collected from the channel bed (T5) and an adjacent bank (Table DR3).

RESULTS

OSL dating of paleochannels on the gravel fan suggests that these reaches change location through avulsion on timescales of 10^3-10^4 years (Fig. 1). This is consistent with satellite imagery showing that the gravel channel belt position was stable between 1984 and 2016 (Fig. DR5.1). In contrast, meander migration rates immediately downstream of the GST are up to ~450 m per year (Fig. DR5.2).

Sand is transported throughout the year (Fig. 2A). Gravel that makes up the bar surfaces in the gravel reach (D_{50} = 65 mm) is moved when discharge exceeds ~5,100 m^3/s. This threshold is exceeded annually based on discharge records. Coarser gravel (D_{50} = 231 mm) on the bed of the dry bifurcation point requires a discharge of ~31,500 m^3/s if the form drag correction (β) is 0.5, which corresponds to a 1-in-7,000 year discharge (Fig. 2B). Increasing β to 0.6 reduces the threshold to ~23,500 m^3/s, which corresponds to a 1-in-500 year discharge. Values of β reported for gravel-bed channels typically vary between 0.5 and 0.6 (Venditti and Church, 2014).

Suspended sediment samples were collected during a moderate monsoon flow (4,500 m^3/s, return interval ~1 year; Fig. 2b). In the gravel reach (T1 to T4), suspended sediment grain size (Fig. 3A) shows a slight overall downstream decrease, and a less prominent reduction in concentration (Fig. 3B). Both show minor variations with flow depth. In the sand reach (T5), concentration and D_{50} are higher in the lower 20% of the water column compared to the gravel reach and the vertical gradients are steeper (Fig. 3A & B). Suspended sand flux remains comparable between the bifurcation and upstream of the GST at ~0.3-0.4 Mt/d (T2-4; Fig. 3C). In the sand reach, the instantaneous sediment flux is an order of magnitude higher at ~3.7-4.5 Mt/d.

DISCUSSION

Changes in Channel Mobility

Upstream of the GST there is minimal lateral migration of the channel belt across the floodplain. Major changes in channel configuration in the gravel-bed portion of the river appear to be driven by apex-avulsion (Leddy et al., 1993), where channel thalweg sinuosity drives inner-bend lateral accretion and outer-bend erosion resulting in cycles of channel plugging and abandoned channel re-occupation. OSL dating and calculations of threshold for gravel bed entrainment at the bifurcation suggest timescales associated with channel avulsion are ~400 to 7,000 years. In contrast, downstream of the GST, high rates of channel migration driven by lateral meander migration are enhanced by the presence of a poorly consolidated, low clay-content floodplain material that is devoid of deep-rooted vegetation. Even under low flow conditions, both bed and bank material are mobilized, enhancing sand delivery to the bed and lower portion of the water column. Anecdotally, during our 3-hour survey of site T5, we observed the adjacent sand bank retreat by ~ 3 meters. The increase in D_{50} in the near bed sample at T5 may reflect the fact that material eroded from the bank is coarser than the material carried in suspension through the gravel reach at that time. These coarser sediments may have been transported and deposited under larger flood discharges, in contrast to the conditions under which the channel was sampled. The coarser grain sizes at T5 were absent from samples in T1-T4, suggesting this observation was unlikely a simple function of grain size sorting associated with the development of a Rouse-like suspended bed material profile. These combined results suggest that the location of the GST controls channel migration of alluvial rivers downstream of the Himalayan and possibly other mountain fronts.

Temporal Changes in Sediment Transport

The absence of grain size or concentration gradients for profiles collected in the gravel reach suggests that sand is transported here as wash load. The steep concentration and grain size gradients at T5 are consistent with theoretical models indicating this material is sourced from the bed (Rouse, 1936). The significant increase in sediment flux and grain size across the GST (T4 to T5) coincides with observed changes in channel mobility. It is suggested that the augmented sediment flux in the sand reach is sourced from the banks. The interpretation that sand is no longer transported as wash load at T5, is consistent with wash load deposition patterns modelled by Lamb and Venditti (2016), and direct observations from the Fraser River (Venditti and Church, 2014; Venditti et al., 2019).

Mass continuity dictates that the increase in sediment concentration across the GST cannot be a persistent feature, given the aggrading nature of the Ganga Plain (e.g. Dingle et al., 2016). Our flux estimates are from moderate monsoonal flow conditions. During peak seasonal flow conditions, shorter lived and more intense floods occur, during which pulses of sand would be delivered out of the mountains and into the gravel reach. A further increase in suspended sand load within the gravel reach is also expected due to the breakdown of the bed surface armor layer and associated release of finer matrix material. As flow recedes, the gravel bed and banks are no longer mobile and sand transport is reduced through the gravel-bed reach (Fig. 4). Downstream, the sand channel is still capable of reworking flood flow deposits (even under lower flows) via lateral channel migration. The increase in sediment grain size, concentration and instantaneous flux below the GST likely reflects continuous reworking and intermittent cannibalization of bank material deposited by past floods. This sediment is likely only translated a short distance before being deposited on downstream point bars and integrated back into the bank as the channel migrates laterally and the bank accretes vertically.

Implications on Sediment Flux Estimates

In many systems, cohesive bank material and root networks limit lateral migration but sediment storage and recycling is observed (e.g. Venditti et al., 2015), suggesting that our observations are not unique to the Karnali River. An increase in suspended sediment concentration has been observed across the GST in the Fraser River, British Columbia (Venditti et al., 2015). Following a peak spring freshet flow in June 2007, observations of suspended sediment across the Fraser GST revealed that the total flux of sand (bed load and suspended load) increased downstream from 0.044 Mt/d to 0.127 Mt/d (Data Repository; Table DR4). However, unlike the Karnali, the Fraser River is laterally constrained; the increase in sediment flux occurs because of changes in sand storage across the GST under different flow stages. During high flows a thick deposit of sand, up to 10 m thick, is mobilized at the upstream limit of the GST and diffused downstream. The storage at the upstream limit has been observed to fill again as flow wanes (Venditti et al., 2015).

Both lateral channel migration and vertical filling and depletion of sand across the Karnali and Fraser River GSTs is reflected by a counter-intuitive downstream increase in sediment flux under moderate and high flow conditions, respectively. This highlights potential limitations in the use of temporally limited, local sediment sampling downstream of mountain ranges when calculating continental-scale sediment fluxes and denudation rate estimates. Sediment flux estimates using comparable methods by Lupker et al. (2011) on the Ganga River at Harding Bridge, Bangladesh, were 7.51 Mt/d under peak flow conditions (44,800 m^3/s). Our measurements collected under moderate monsoonal flow conditions (~2,000 m^3/s) are >50% of this value, despite the Karnali basin making up <5% of the Ganga catchment area upstream of Harding Bridge. Our results indicate that downstream increases in suspended sediment concentration and grain size arise due to remobilization of bank material through lateral migration, suggesting that sediment flux measurements in such settings are enhanced by this process. To confirm, long-term records capturing sediment flux under a range of flow conditions are required.

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FIGURE CAPTIONS

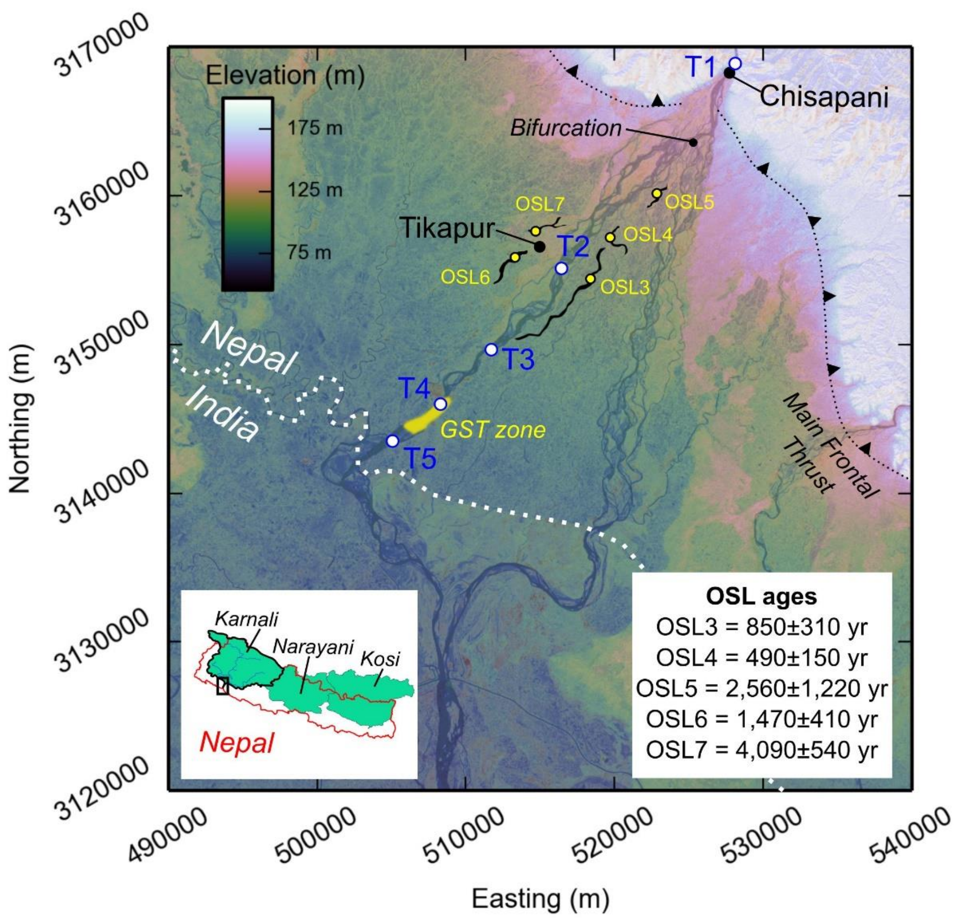

Figure 1. Study area showing suspended sediment sampling locations (T1-T5) and the gravel-sand transition extension on the Karnali River. Paleochannels (black lines) on the fan and optically

stimulated luminescence dates are labelled (Data Repository for full methods). Data sources: 30 m Shuttle Radar Topography Mission Digital Elevation Model (coordinates in UTM Zone 43N) and Sentinel-2 satellite imagery (October 26, 2016).

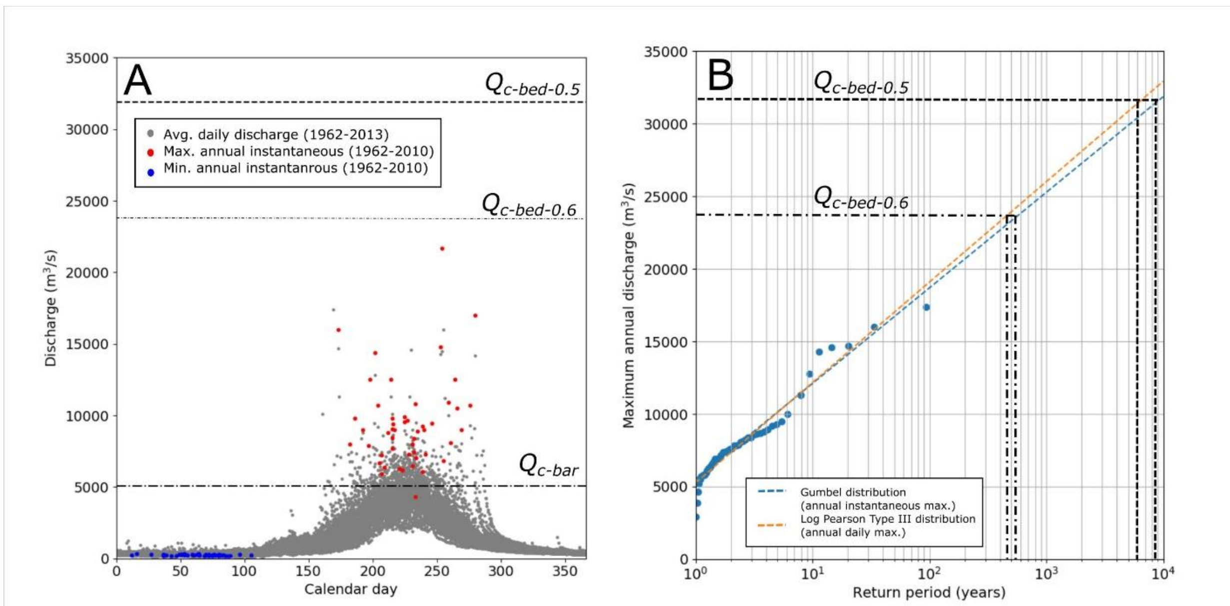

Figure 2. A) Discharge at Chisapani gauging station from 1962 to 2010. B) Projected return interval of discharges. Discharges required to mobilize the gravel-bar surface ($Q_{c\text{-}bar}$) and the median gravel-bed size at the bifurcation using β=0.5 ($Q_{c\text{-}bed\text{-}0.5}$) and β=0.6 ($Q_{c\text{-}bed\text{-}0.6}$), where β is the form drag correction used (see Data Repository), are shown. The discharge required to mobilize sand is 3-4 m^3/s.

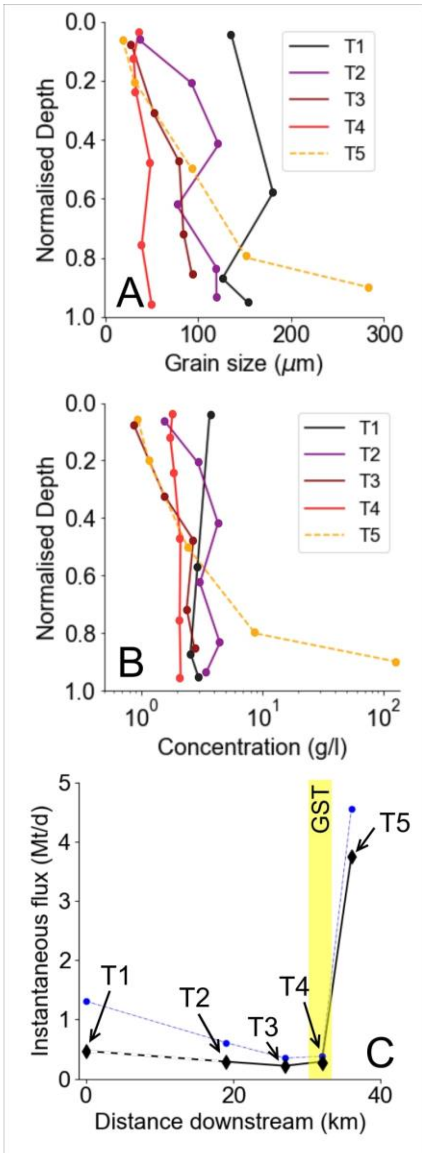

Figure 3. A) Median grain size at each vertical. B) Suspended sediment concentration at each vertical. C) Instantaneous sediment flux estimates. The black line and diamonds represent sediment fluxes calculated from depth-averaged Rouse profile concentrations, the blue circles and dashed lines represent fluxes calculated from depth-averaged measured concentrations. T1 is upstream of the bifurcation so some sediment is routed through the east branch before T2 (dashed line between T1 and T2). Channel depths are normalized: see Fig. DR2.1-2.5 for absolute depths.

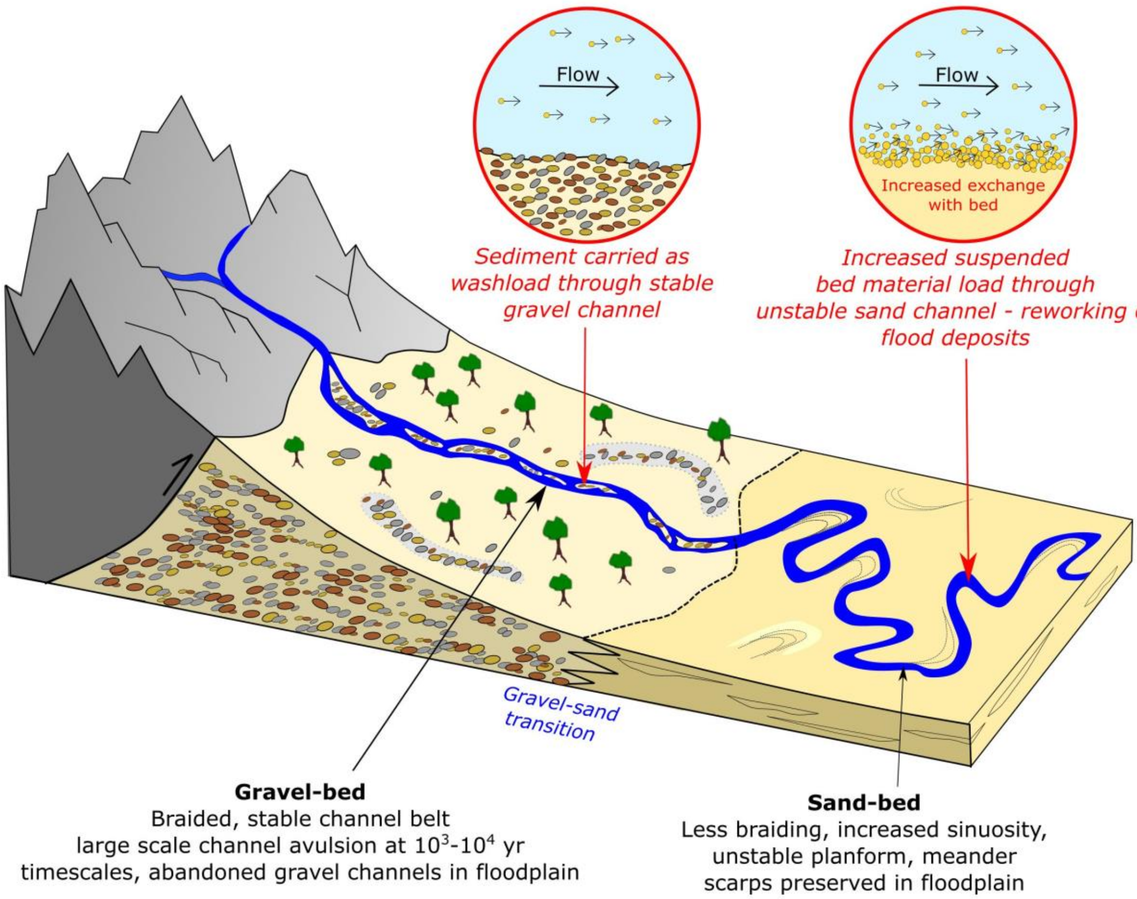

Figure 4. Summary of changes in channel morphology, migration style (black text) and modes of sediment transport (red text) across the Karnali gravel-sand transition under low to moderate flow conditions.